HYDRAULIC PERFORMANCE CURVES
Culverts Operating Under Inlet Control

In selecting a culvert size, the designer is basically concerned with providing adequate pipe capacity to carry a design discharge without exceeding an allowable headwater depth at the culvert inlet. If this is to be accomplished with an efficient structure consistent with economy, adequacy and necessary installation requirements, the design must be based on sound hydraulic principles.

The many hydraulic design procedures available for determining the required size of a culvert vary from empirical formulas to a comprehensive mathematical analysis. Most empirical formulas, while easy to use, do not lend themselves to proper evaluation of all the factors that affect the flow of water through a culvert. The mathematical solution, while giving precise results, is time consuming. A systematic and simple design procedure for the proper selection of culvert size is provided by Hydraulic Engineering Circular No. 5, prepared by the Hydraulics Branch, Bridge Division, Office of Engineering and Operations of the Bureau of Public Roads.

Because the flow characteristics of a culvert, and thus the hydraulic capacity, are often controlled by inlet or outlet conditions, Circular No. 5 presents inlet control and outlet control nomographs for the selection of the more common types of culverts. The nomographs take into consideration the physical characteristics of the pipe, such as slope, length, surface roughness, size and shape of the culvert and inlet geometry. Although the nomographs provide for the ready selection of culvert size and type, the design procedures presented in Circular No. 5 still require a trial and error solution.

Inlet control performance curves have been developed from the inlet control nomographs included in Circular No. 5 and are presented here as a design aid for culverts flowing with inlet control. For a given design discharge \( Q \) and allowable headwater \( HW \), the minimum size culvert operating under inlet control can be read directly from the curves. It is only necessary to check the headwater for outlet control in accordance with the procedure outlined in Circular No. 5 and use the higher value to determine the type of control and proper culvert size required. Much of the time-consuming trial and error work involved in using the inlet control nomographs is eliminated and a culvert size is established for a comparison with the outlet control condition. It should be noted that the figures are for a projecting inlet condition. For other entrance types, the headwater depth from the inlet control curves should be multiplied by the factors shown in Table I and the resulting headwater depth used with the design discharge.

An examination of the charts shows the discharge advantage of concrete pipe entrances operating with inlet control. Figures 2 through 5 indicate that a concrete pipe one size smaller than corrugated metal pipe is warranted in the size range of 21-inch to 78-inch diameter concrete pipe. For concrete pipe sizes from 84-inch to 126-inch diameter, Figures 6 through 8 indicate that a concrete pipe two sizes smaller than corrugated metal pipe is warranted. These size differentials may increase if outlet control governs, since this condition must take into account the roughness of the pipe. The following examples illustrate the use of the inlet control performance curves:

<table>
<thead>
<tr>
<th>TABLE I: Conversion Factors To Be Applied To Headwater Depth For Entrance Types Other Than Projecting</th>
</tr>
</thead>
<tbody>
<tr>
<td>Headwater Depth</td>
</tr>
<tr>
<td>Full Headwall</td>
</tr>
<tr>
<td>Circular</td>
</tr>
<tr>
<td>HW &lt; D</td>
</tr>
<tr>
<td>D &lt; HW &lt; 1.5 D</td>
</tr>
<tr>
<td>HW &gt; 1.5 D</td>
</tr>
</tbody>
</table>
**EXAMPLE 1**

**Given:**
- Design discharge: \( Q = 260 \) cubic feet per second
- Headwater at inlet: \( AH = 8.00 \) feet
- Length of culvert: \( L = 100 \) feet
- Slope of culvert: \( S_v = 0.01 \) feet per foot = 1.00%
- Tailwater elevation: \( TW = 4 \) feet
- Inlet condition: Projecting

**Find:**
- Size of pipe required

**Solution:**
- Find the intersection of \( Q = 260 \) cubic feet per second and \( HW = 8 \) feet on Figure 5. The first sizes of concrete and corrugated metal pipe to the right of this intersection are the minimum sizes that require an inlet control headwater equal to or less than the allowable 8 feet.
- The sizes, read from the chart, and the required inlet control headwater depths are:
  - 66-inch concrete pipe: \( HW = 7.70 \) feet
  - 78-inch concrete pipe: \( HW = 7.35 \) feet

From Circular No. 5, a check of the above sizes of pipe found satisfactory for inlet control condition results in the following required headwater for the outlet control condition:
- 66-inch concrete pipe: \( HW = 6.70 \) feet
- 78-inch concrete pipe:
  - Standard corrugations: \( HW = 7.00 \) feet
  - Structural plate: \( HW = 7.50 \) feet

**Answer:**
- The following sizes of pipe will carry the design discharge within the allowable headwater depth of 8 feet:

**EXAMPLE 2**

**Given:**
- Same conditions as Example 1, except:
  - Length of culvert: \( L = 100 \) feet
  - Slope of culvert: \( S_v = 0.003 \) feet per foot = 0.30%

**Find:**
- Size of pipe required

**Solution:**
- The sizes required for inlet control are the same as those required in Example 1, since length and slope of a culvert do not affect the inlet control condition. However, a check of the outlet control condition, using Circular No. 5 design procedures, results in the following table of required headwaters.
- As shown, a check of the outlet control conditions results in some changes of the pipe sizes required for inlet control.

**Answer:**
- The following sizes of pipe will carry the design discharge within the allowable headwater depth of 8 feet:

<table>
<thead>
<tr>
<th>Pipe Size</th>
<th>Pipe Type</th>
<th>Required Headwater</th>
<th>Required Headwater</th>
<th>Controlling Condition</th>
<th>Controlling Condition</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>66&quot;</td>
<td>Concrete</td>
<td>7.00 ft.</td>
<td>7.80 ft.</td>
<td>Outlet</td>
<td>Outlet</td>
<td>O.K.</td>
</tr>
<tr>
<td>78&quot;</td>
<td>Metal (std. corrugations)</td>
<td>7.35 ft.</td>
<td>8.80 ft.</td>
<td>Outlet</td>
<td>Outlet</td>
<td>N.G. (too high)</td>
</tr>
<tr>
<td>84&quot;</td>
<td>Metal (std. corrugations)</td>
<td>7.00 ft.</td>
<td>7.75 ft.</td>
<td>Outlet</td>
<td>Outlet</td>
<td>O.K.</td>
</tr>
<tr>
<td>84&quot;</td>
<td>Metal (structural plate)</td>
<td>7.00 ft.</td>
<td>9.10 ft.</td>
<td>Outlet</td>
<td>Outlet</td>
<td>N.G. (too high)</td>
</tr>
<tr>
<td>90&quot;</td>
<td>Metal (structural plate)</td>
<td>6.65 ft.</td>
<td>8.10 ft.</td>
<td>Outlet</td>
<td>Outlet</td>
<td>N.G. (too high)</td>
</tr>
<tr>
<td>96&quot;</td>
<td>Metal (structural plate)</td>
<td>6.30 ft.</td>
<td>7.40 ft.</td>
<td>Outlet</td>
<td>Outlet</td>
<td>O.K.</td>
</tr>
</tbody>
</table>

In Example 2, selection of the required sizes of pipe could not be made from the use of the inlet control curves alone. However, the use of the inlet control curves should serve as a design aid by eliminating trial and error selection of sizes to be investigated.

**FIGURE 1:** Inlet Control Performance Curves – Circular Concrete Pipe and Corrugated Metal Pipe

**FIGURE 2:** Inlet Control Performance Curves – Circular Concrete Pipe and Corrugated Metal Pipe